Journal of Environmental Monitoring

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Cite this: *J. Environ. Monit.*, 2011, **13**, 721

www.rsc.org/jem

PAPER

Stream water nutrient enrichment in a mixed-use watershed

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Received 20th October 2010, Accepted 16th December 2010
DOI: 10.1039/c0em00584c

Eutrophic conditions, in both saline and freshwater systems, result from nutrient export from upstream watersheds. The objective of this study was to quantify the surface runoff losses of nitrate-nitrogen (NO_3-N), total nitrogen (TN), dissolved reactive phosphorus (DRP), and total phosphorus (TP) resulting from prevailing practices on a managed golf course. Inflow and outflow discharge waters on a sub-area of Northland Country Club (NCC) located in Duluth, Minnesota were measured for both quantity and quality from April through November from 2003 to 2008. Nutrient losses were detectable throughout the year, had a seasonal trend, and routinely exceeded recommended levels to minimize eutrophication. The median outflow TN concentration (1.04 mg L^{-1}) was significantly greater ($p < 0.05$) than the median inflow (0.81 mg L^{-1}) concentration. Similarly, the median outflow TP concentration (0.03 mg L^{-1}) was significantly greater ($p < 0.05$) than the median inflow concentration (0.02 mg L^{-1}). Maximum recorded concentrations during the study period were 1.9 mg L^{-1} NO_3-N, 3.93 mg L^{-1} TN, 0.34 mg L^{-1} DRP, and 1.11 mg L^{-1} TP. Mean annual export coefficients at NCC were 0.7 kg ha^{-1} NO_3-N (1.7% of applied), 4.43 kg ha^{-1} TN (10.7% of applied), 0.14 kg ha^{-1} DRP (2.6% of applied), and 0.25 kg ha^{-1} TP (4.6% of applied). The findings of this study highlight the need for adopting conservation practices aimed at reducing offsite nutrient transport.

Introduction

Hypoxic (<2 mg L^{-1} dissolved oxygen) and anoxic (zero oxygen) areas in coastal marine and freshwater bodies worldwide continue to be a major environmental concern. For example, hypoxic areas in the Gulf of Mexico,[1] Baltic Sea,[2] Black Sea,[3] Chesapeake Bay,[4] China Sea,[5] and Great Lakes[6] continue to increase in size and have deleterious effects on fisheries and ecosystem function. In the case of coastal waters, excess nitrate-nitrogen has historically been cited as the primary driver; however, recent evidence suggests that phosphorus may also play a critical role in the development of these marine eutrophic areas.[7] Excess phosphorus has generally been identified as the problem nutrient in freshwater systems.[6]

In addition to near shore sources of nutrient inputs,[8,9] export from upland watersheds have been cited as major contributors of excess nutrients.[10,11] Generally, intense crop production agriculture has been the primary focus of excess nutrients leading to hypoxic conditions. However, industry and increased urbanization within contributing watersheds are also responsible for surface and subsurface losses of nutrients.[12] Reducing nutrient losses from all sources is required to control hypoxia.[13]

In the urban landscape golf courses are the most intensively managed land use,[14] leading to the perception that golf courses significantly contribute to environmental degradation.[15,16] Nutrient applications on golf courses are used to promote healthy, dense turfgrass that (1) resists pest infestations; (2) reduces runoff and sediment loss; (3) has the appropriate color, texture, and density expected for recreational turf; and (4)

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Environmental impact

Eutrophication of surface water bodies worldwide continues to be a significant issue. Identifying the sources of nutrients leading to these eutrophic conditions is necessary for development and deployment of best management practices designed to mitigate nutrient losses. We measured water quantity and quality for a six year period at a managed turf system in Duluth, MN to quantify the surface losses of both soluble and total nutrients. Nutrients were detectable throughout the year, had a seasonal trend, and routinely exceeded recommended levels to minimize eutrophication. These findings highlight the need for watershed stakeholders to consider all land uses within the watershed and develop and adhere to management plans that integrate practices for managed turf systems.

withstands wear and compaction associated with moderate foot traffic. Due to its dynamic characteristic in the soil, available nitrogen levels tend to decrease over time and, therefore, require regular additions to maintain sufficient, site-specific fertility levels. Phosphorus usually enhances the rate of turfgrass establishment from seeds or vegetative plantings. Phosphorus is generally needed during the start-up or green-up phase but subsequent applications may be reduced. Nitrogen is applied to maintain adequate turf growth, density, and color. Application rates across golf courses vary due to climate, site conditions, turf varieties, and expectations of color and density.

Annually, golf courses in the US apply an average of 173 kg ha^{-1} of nitrogen and 73 kg ha^{-1} of phosphorus to the course.[17] Carrow *et al.* reviewed the range of monthly to annual application of nitrogen and phosphorus for turfgrass management.[18] They concluded that application rates vary by maintenance budget, turf variety (cool *vs.* warm season), and soils.

The number of golf course watershed scale nutrient studies is limited. Most but not all of these studies are based on periodic grab sample collection from the course.[19–23] Some of those studies only report concentrations;[19,20] while, others report both load and concentrations.[21–23] One study investigated nutrient transport in both storm event runoff and baseflow.[23]

Quantitative water quality studies from watershed scale golf facilities are sparse. However, there exists a significant need for watershed scale turf studies in multiple climatic zones,[24] especially to quantify the role of these systems in the larger ecosystem. The objective of this study was to quantify the semi-long term watershed scale losses of nitrogen and phosphorus resulting from typical golf course management in the humid, north central United States. Having an understanding of these losses will permit the identification of management practices and strategies necessary to reduce stream loading and address downstream hypoxic conditions.

Methods and materials

Experimental site

The experimental site was a 21.8 ha sub-area of Northland Country Club (NCC) golf course located in Duluth, MN. The study area contained 7 greens (0.3 ha), 8 tees (0.5 ha), 10.5 fairways (3.95 ha), grass roughs (8.1 ha), and 8.95 ha of unmanaged mixed northern hardwoods (Fig. 1). A small stream enters the study area at the inlet and empties into a small detention pond, once used for irrigation. After the water leaves the pond it meanders 700 meters through the study area until it exits at the outflow collection site and eventually into Lake Superior. There is a 37 m elevation change across the study area with slopes ranging from 3 to 25%. Approximately 80 ha of low density housing and forested area feed the inflow site. A small area of typical urban housing is located on the east side of the inflow portion of this upper watershed.

NCC soils are characteristic of re-worked lacustrine clay deposits, moderately deep (3 to 6 m) over bedrock. The dominant soil on NCC is the Sanborg (fine, mixed, active, frigid, Oxyaquic Glossudalfs)–Badriver (fine, mixed, active, frigid Aeric Glossaqualfs) complex (Table 1). Previous references to the soils located on NCC identified the soils as Cuttre, Ontonagon, and Bergland

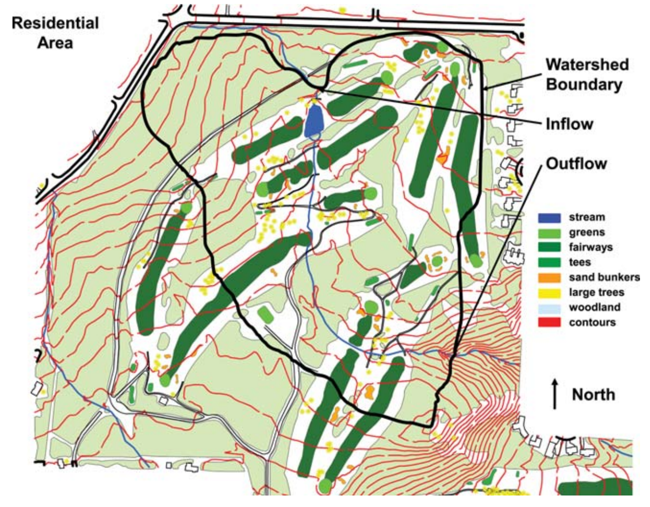

Fig. 1 Plan view of NCC golf course and study area.

soils; however, more recent soil surveys have identified the soils as Sanborg–Badriver complex. All of these soils have very similar morphological, chemical, and physical characteristics. The parent material is re-worked, noncalcareous clayey lacustrine deposit over calcareous lacustrine clays. Perched water table conditions on the site are common and are caused by dense subsurface horizons and fine-textured soils.

NCC is located in a temperate-continental climatic region. The area is characterized by warm, moist summers and cold, dry winters. The average monthly maximum summer temperature (May–August) ranges from 16 °C to 25 °C while the average monthly maximum winter temperature (December–March) ranges from −9 °C to 0 °C. Average annual (1949–2008) precipitation measured at the Duluth International Airport during the period of April–November was 648 mm (standard deviation = 123 mm). The streambed at the inlet and outlet is typically frozen from the end of November through the end of March.

NCC is managed at a moderate to intense level. Greens and tees were seeded with creeping bentgrass (*Agrostis palustris* Huds. *Agrostis stolonifera* L.). Fairways were primarily creeping bentgrass with some Kentucky bluegrass (*Poa pratensis* L.). The roughs were a mixture of annual bluegrass (*Poa annua* L.) and Kentucky bluegrass. During the study period the course did go through one change in superintendents slightly altering the approach to management.

Nutrient application at NCC is considered moderate and is a combination of organic, bio-stimulant, slow release, and fast release formulations applied by both dry broadcast and spray techniques. More recently the approach has been to move toward an organic approach with reduced applications (Table 2). Nitrogen fertilization is greatest in May and June and gradually decreases through the remainder of the playing season. Similarly, phosphorus application is greatest in May; phosphorus application throughout the remainder of the management season is similar but generally less than May applications.

Data collection and uncertainty

Hydrology and nutrient export data were collected from a subarea of Northland Country Club (NCC) located in Duluth,

Table 1 Soil mapping units, extent of coverage, and NRCS hydrologic soil group classification for soils located in the study areas of MWMGC and NCC[a]

Soil mapping unit	Dominant texture	NRCS hydrologic soil group	Extent of unit/ha	% of total area
Barto-Greysolon-rock outcrop complex, 0% to 18% slope	Gravelly sandy loam	D	1.7	8.0
Sanborg–Badriver complex, 3% to 18% slope	Clay	D	20.1	92.0

[a] Data extracted from NRCS soil survey.

Minnesota, USA. Discharge and water quality samples were collected by a combination of grab samples and automated sample collection. In the summer of 2002, two three foot H-flumes with stilling wells and approach sections were installed in the stream that bisects the study area (Fig. 1). One flume was positioned at the inflow while another was placed at the outflow. The H-flumes were instrumented with Isco 4230 bubblers programmed to record stage on 10 minute intervals. Stage was converted to discharge by using the standard three foot H-flume stage–discharge rating curve. Precipitation was collected on site using Isco 674 tipping bucket rain gauges. Rain gauges were located at both the inlet and outlet data collection sites for backup purposes. Rainfall was assumed uniform over the study area. Isco 6700 automated samplers were programmed to collect discrete flow proportional samples every 132 m^3 (35 000 gallons). Samples were collected in 350 ml glass bottles and transported to the laboratory following collection, at a minimum once per week but typically twice per week. Samples were stored at 4 °C and analyzed within 28 days after collection.

Based on methods outlined by Harmel *et al.*, the estimated error in discharge measurement for NCC was ±3%.[25] In addition to error in the discharge measurements, error may also be introduced in the precipitation measurements. Tipping-bucket rain gauges have been shown to lag measurements from standard gauges from 5% to 10%.[26,27] The level of uncertainty associated with the data used in this study is consistent with the low end of published and expected errors for field and watershed scale hydrology studies, suggesting the results obtained from this study are reliable and of high quality.[25]

Table 2 Location and amount of elemental nitrogen and phosphorus applications at Northland Country Club (2003–2008)

	Greens	Tees	Fairways	Roughs	Total (aerial weighted)
Nitrogen/ kg ha^{-1}					
2003	67.4	132.9	93.4	92.9	55.6
2004	112.8	264.5	117.4	48.9	46.9
2005	66.3	160.4	107.1	24.4	33.0
2006	63.2	160.0	101.0	43.5	39.0
2007	143.4	63.7	68.5	32.3	27.9
2008	132.8	134.9	37.7	95.4	47.4
Average	97.7	152.7	87.5	56.2	41.6
Phosphorus/ kg ha^{-1}					
2003	26.1	60.2	25.8	6.3	8.8
2004	26.9	51.7	27.4	—	6.5
2005	25.3	28.6	32.7	—	6.9
2006	7.5	12.7	21.1	0.6	4.4
2007	46.5	6.7	9.7	1.4	3.1
2008	39.5	32.2	7.2	—	2.6
Average	28.6	32.0	20.6	2.8	5.4

Chemical analysis

Following collection, samples were filtered through a 0.7 μm pore diameter glass fiber filter, stored below 4 °C and analyzed within 28 days for dissolved nutrients. Concentrations of NO_3 + NO_2-N and PO_4-P were determined colorimetrically by flow injection analysis using a Lachat Instruments (Milwaukee, WI) QuikChem 8000 FIA Automated Ion Analyzer and application of the phenol–hypochlorite, copperized-cadmium reduction and ascorbic acid reduction methods, respectively.[28] Total nitrogen (TN) and total phosphorus (TP) analyses were performed concurrently on unfiltered samples following alkaline persulfate oxidation with subsequent determination of NO_3-N and PO_4-P.[29] From this point forward NO_3 + NO_2-N will be expressed as NO_3-N. Here, PO_4-P is used synonymously with dissolved reactive phosphorus (DRP) and will be designated from this point forward as DRP.

Loads were calculated by multiplying the analyte concentration by the measured water volume for that respective sample. The volume of water associated with any one sample was determined using the midpoint approach; the temporal midpoint between each sample was determined and the volume of water calculated for that time duration. The analyte concentration was assumed to be representative over that specific flow duration.

Statistical analysis

All statistical analyses were conducted with SigmaStat 3.5 statistical software[30] and methods outlined by Haan.[31] Normality was tested using the Kolmogorov and Smirnov test and a significance level equal to 0.05. Distributions were generally not normally distributed, thus median values collected at the inflow and outflow points were tested using the Mann–Whitney nonparametric statistic with a significance level of 0.05.

Results

Data were collected during the hydrologic active time from April through November for calendar years 2003 through 2008. Measured on-site precipitation for each year was less than the 648 mm normal (30 year average) precipitation recorded at the Duluth International Airport, some 19 km west of the study site (Table 3). Differences in annual on-site precipitation and airport precipitation ranged from 5% in 2007 to 34% in 2003.

Table 3 Measured precipitation, intensity, and discharge for upland site, upland plus NCC, and NCC during data collection period April through November

						Upland		Upland + NCC		NCC		
Year (Apr–Nov)	On-site rainfall (P)/mm	NWS airport rainfall/mm	Aerial weighted irrigation/mm	Max. int./mm h^{-1}	Max. 24 h rainfall/mm	Disch. (Q)/mm	Q/P (%)	Disch. (Q)/mm	Q/P (%)	Disch. (Q)/mm	Q/P (%)	$Q/(P+I)$ (%)
2003	352.6	531	51.3	18.5	37.1	71.8	0.20	92.8	0.26	170.2	0.48	0.42
2004	482.1	564	48.9	22.3	51.3	107.3	0.22	143.4	0.30	276.1	0.57	0.52
2005	558.8	654	69.0	23.9	74.9	166.3	0.30	196.5	0.35	307.3	0.55	0.49
2006	417.6	517	64.0	19.1	50.5	91.0	0.22	110.0	0.26	179.8	0.43	0.37
2007	567.2	594	45.0	33.8	71.9	167.5	0.30	202.4	0.36	330.3	0.58	0.54
2008	644.9	705	26.7	21.6	53.6	285.0	0.44	342.8	0.53	555.0	0.86	0.83

On-site measured precipitation generally followed a bimodal distribution with peaks in spring and fall (Fig. 2). Measured discharge followed a similar bimodal pattern. Discharge in early spring (April) often exceeded precipitation amounts. Conversely, discharge in summer months was generally less than precipitation. Annual discharge from the golf course, expressed as a fraction of precipitation (Q/P), ranged from 0.43 to 0.86 (Table 3). When factoring in the entire drainage area (golf course plus upland), Q/P ratios ranged from 0.26 to 0.53 (Table 3).

Nutrient specific median inflow and outflow concentrations across all years were significantly different ($p < 0.05$) (Fig. 3). Inflow nitrate-nitrogen (NO_3-N) concentrations ranged from <0.004 to 1.94 mg L^{-1} with a median concentration of 0.28 mg L^{-1}. Outflow NO_3-N concentrations ranged from <0.004 to 1.9 mg L^{-1} with a median of 0.25 mg L^{-1}. Total nitrogen (TN) inflow concentrations ranged from <0.004 to 3.14 mg L^{-1} while outflow TN concentrations ranged from <0.004 to 3.93 mg L^{-1}. Median inflow TN concentration was 0.81 mg L^{-1} compared to an outflow TN concentration of 1.04 mg L^{-1}. Dissolved reactive phosphorus (DRP) concentrations at the inflow ranged from <0.001 to 0.26 mg L^{-1} with a median concentration of 0.01 mg L^{-1}. Similarly, outflow DRP concentrations ranged from <0.001 to 0.34 mg L^{-1} and also had a median of 0.01 mg L^{-1}. Total phosphorus (TP) concentration measured at the inflow ranged from <0.001 to 0.48 mg L^{-1} compared to a range of <0.001 to 1.11 mg L^{-1} TP at the outflow. The median inflow TP concentration was 0.02 mg L^{-1} compared to 0.03 mg L^{-1} at the outflow.

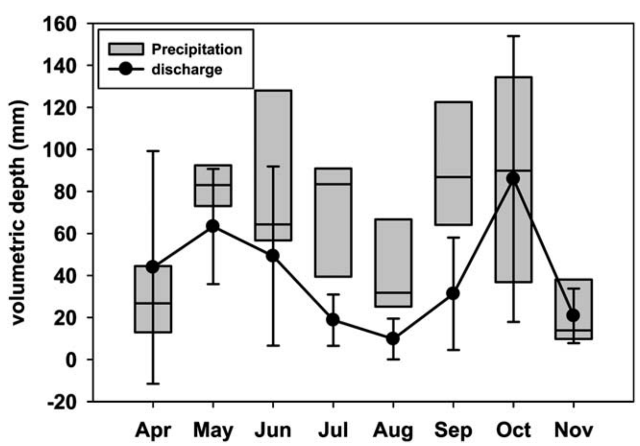

Fig. 2 Monthly distribution of precipitation and discharge recorded at NCC (2003–2008).

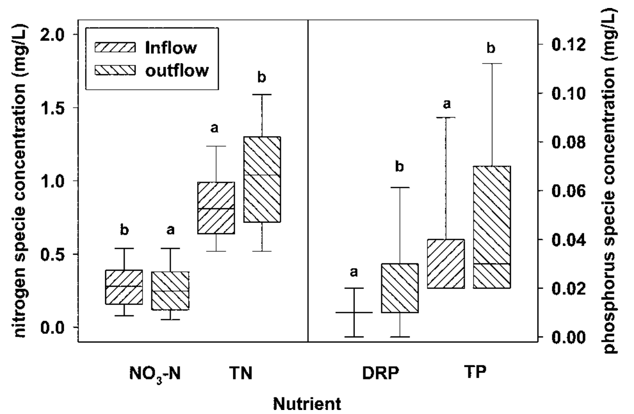

Fig. 3 Box and whisker plots of inflow (n = 1014) and outflow (n = 1317) concentrations measured at Northland Country Club from April 2003 to November 2008. Boxes are bound by 25th and 75th percentile, while whiskers represent the 10th and 90th percentile. Lines in box correspond to the median. For each nutrient species, different letters over the whiskers indicate statistically significant differences ($p < 0.05$) in median concentrations for that specific nutrient species.

Nutrient concentrations measured in the inflow and outflow also varied seasonally. Inflow NO_3-N concentrations were significantly greater than outflow concentrations in all months except July and August (Fig. 4). TN concentrations by month were always greater in the outflow compared to the inflow. Median monthly concentrations of both DRP and TP were consistently greater in the outflow compared to the inflow (Fig. 4).

Mean annual export of NO_3-N resulting from the course was 0.7 kg ha^{-1} (Table 4). TN losses from NCC were 4.43 kg ha^{-1} (Table 4). The majority of the NO_3-N and TN losses were measured during May, September, and October (Fig. 5). Expressed as a percentage of applied nitrogen, the NO_3-N losses were 1.7% while TN losses were 10.7%.

Mean annual DRP losses were 0.14 kg ha^{-1} while TP losses were 0.25 kg ha^{-1} (Table 5). As with nitrogen, the majority of losses occur in the May green-up phase and in fall (September and October) when greater discharge volumes were measured (Fig. 6). Loss of DRP expressed as a percentage of applied elemental P was 2.6%. TP losses were 4.6% of applied.

Discussion

Hydrology at NCC is a function of winter thaw in the early spring, while convective thunderstorms and frontal systems

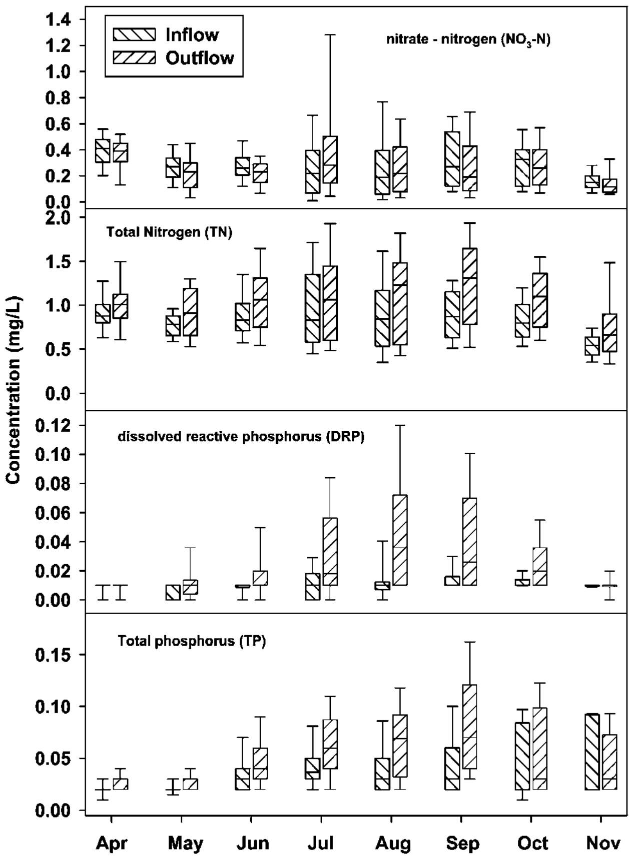

Fig. 4 Box and whisker plots of inflow and outflow nutrient concentrations by month. Boxes are bound by 25th and 75th percentile. Whiskers represent the 10th and 90th percentile. Lines in the box correspond to the median.

Table 4 Annual loading of nitrate and total nitrogen from upland site, upland plus NCC, and NCC during data collection period April through November 2003–2008

Nitrate-nitrogen/kg ha^{-1}	Upland	Upland + NCC	NCC
2003	0.19	0.38	1.07
2004	0.29	0.30	0.33
2005	0.53	0.63	0.99
2006	0.25	0.29	0.41
2007	0.77	0.68	0.33
2008	0.80	0.86	1.07
Annual average	0.47	0.52	0.70
TN/kg ha^{-1}			
2003	—	—	—
2004	0.58	1.05	2.76
2005	1.50	2.22	4.86
2006	0.73	1.11	2.51
2007	1.85	2.45	4.64
2008	2.50	3.55	7.40
Annual average	1.43	2.08	4.43

account for summer and fall discharge. Discharge generally followed the same bimodal distribution as precipitation (Fig. 2). The spring thaw generally lasts into May, thus most precipitation occurring during this period will runoff, increasing the discharge to precipitation (*Q*/*P*) ratios. During the summer months (June through September) evapotranspiration (ET) generally exceeds precipitation. During this period, irrigation is applied to the course to eliminate water stress, creating localized areas of near soil saturation. In October and November, discharge and precipitation are similar, suggesting that ET is minimal, a condition that is likely produced by micro-climates around Lake Superior.

The mean annual *Q*/*P* ratio for the forested and residential upland area (0.28) and upland plus NCC (0.34) was greater than but comparable to the runoff fraction of 0.21 from 42 events from a 38 ha single dwelling residential area in Fresno, CA.[32] The greater discharge ratios reported in the immediate study were a combination of storm event runoff and baseflow while the referenced study was a report of storm event runoff only.

The mean annual *Q*/*P* ratio for NCC (0.53) was substantially greater than the 0.18 *Q*/*P* ratio determined from a 5 yr golf course study in Austin, TX[23] and the 0.17 to 0.34 *Q*/*P* ratio range reported for urban and suburban watersheds around Baltimore, MD.[33] However, the *Q*/*P* ratio at NCC was comparable to the 0.47 runoff fraction reported for a 1.5 year study on a 1.75 ha subarea of a golf course in North Carolina.[34] Runoff from fine textured soils can exceed the predicted runoff using soil hydrologic classifications based on the texture and land use.[35]

Relationship of losses to management and climate trends

Nitrogen concentrations. Significant differences in median inflow and outflow nutrient concentrations (Fig. 3) at NCC were attributed to fertility management and physiographic features of the golf course. Median NO_3-N concentration was slightly but significantly greater ($p < 0.05$) in the inflow waters (0.28 mg L^{-1}) compared to the outflow waters (0.25 mg L^{-1}), suggesting that the segment of stream located on the golf course was able to attenuate a portion of NO_3-N. However, we suspect that during low flow periods a significant amount of denitrification takes place in the pond receiving the inflow waters (Fig. 1); thus, the NO_3-N measured at the outlet during these periods is largely the contribution from the course. To support this hypothesis samples were collected from the pond outflow on a regular basis throughout the study period (Fig. 7). Corroborating this theory is the work of Kohler *et al.*[15] who showed a 97% reduction in NO_3-N loads from discharge waters passing through a wetland at a golf course in Indiana. In that study, storm flow NO_3-N concentrations passing through the wetland were reduced by 87% while baseflow concentrations were reduced by 94%.[15] The NO_3-N reduction in the wetland system was attributed to denitrification.

An investigation of monthly NO_3-N concentrations at the inflow and outflow sites indicates median inflow concentrations are greater in every month except July and August (Fig. 4), when discharge rates are least. During these low flow periods, denitrification in the pond would be exacerbated due to greater residence times.[36] Additionally, July and August coincide with greater amounts of golf course irrigation suggesting that NO_3-N may be entering the stream *via* subsurface drainage. Complementing this hypothesis is the strong connection visually observed between irrigation timing and subsurface drainage flow, greater subsurface drainage flow occurring following irrigation. On an annual basis, 74% of all irrigation applied to greens

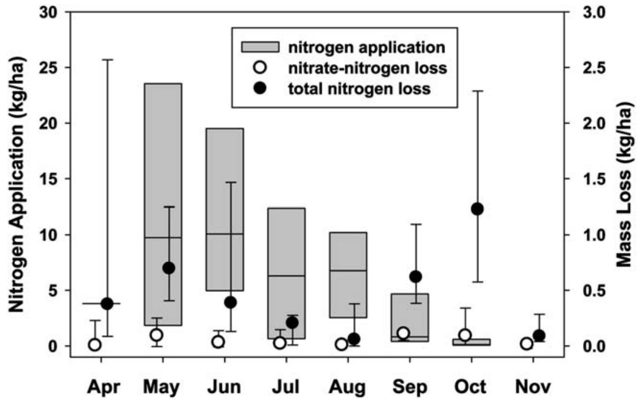

Fig. 5 Monthly distribution of aerial weighted elemental nitrogen application and nitrate-nitrogen and total nitrogen losses from NCC for the period 2003–2008. Lines in box and circles represent median values. Boxes and error bars represent 25th and 75th percentile values.

Table 5 Annual loading of DRP and total phosphorus from upland site, upland plus NCC, and NCC during data collection period April through November 2003–2008

Dissolved reactive phosphorus/kg ha^{-1}	Upland	Upland + NCC	NCC
2003	0.00	0.02	0.11
2004	0.02	0.05	0.17
2005	0.03	0.08	0.25
2006	0.01	0.02	0.07
2007	0.02	0.04	0.11
2008	0.03	0.06	0.13
Annual average	0.02	0.05	0.14
TP/kg ha^{-1}			
2003	—	—	—
2004	0.06	0.11	0.29
2005	0.05	0.11	0.36
2006	0.02	0.04	0.09
2007	0.04	0.07	0.18
2008	0.09	0.16	0.33
Annual average	0.05	0.10	0.25

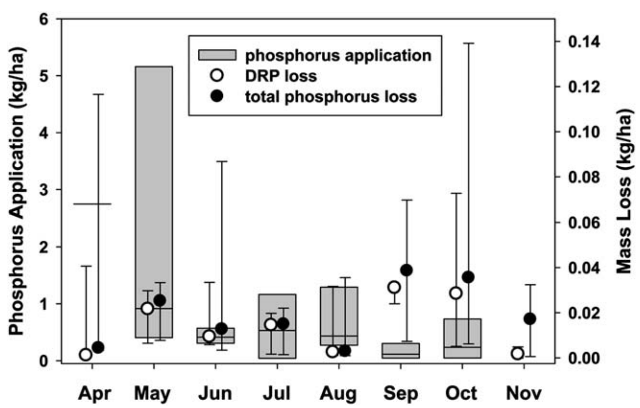

Fig. 6 Monthly distribution of aerial weighted elemental phosphorus application and DRP and total phosphorus losses from NCC for the period 2003–2008. Lines in box and circles represent median values. Boxes and error bars represent 25th and 75th percentile values.

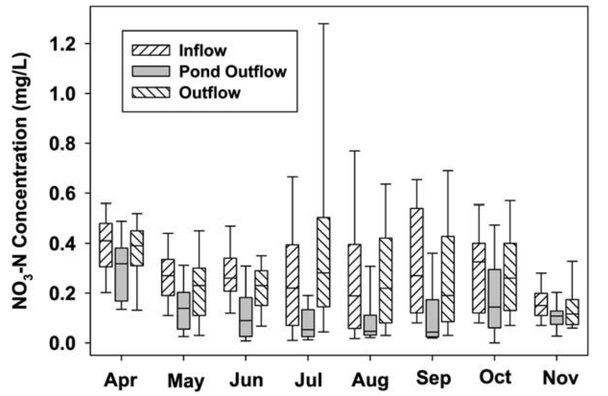

Fig. 7 Box and whiskers plot of NO_3-N concentration measured at inflow, outflow of pond, and outflow of watershed during the study period (2003–2008). Boxes are bound by 25th and 75th percentile. Whiskers represent the 10th and 90th percentile. Lines in the box correspond to the median.

and tees and 78% applied to fairways occur during July and August.

In the early growing season of April, May, and June and during the fall months of September, October, and November, we suspect that some denitrification would still occur in the pond during these periods but the amount would be small relative to other time periods because of greater flows and less residence time. The majority of nitrogen being applied on the golf course during the early growing season is most likely utilized by the grasses on the golf course, as turfgrasses are generally aggressive and efficient users of nitrogen.[37,38] The smaller concentrations in the outflow compared to the inflow also suggest that the stream has some capacity for assimilating some of the nitrogen. The nitrogen attenuation is most likely a result of nitrogen being bound to dissolved organic matter. Dissolved organic matter is promoted by precipitation falling through the forest canopy, forest litter, and turfgrass thatch, and chronically wet clayey soils.[39] It also explains why monthly TN concentrations are always greater in the outflow samples compared to the inflow samples.

Greater inflow NO_3-N concentrations in September, October, and November coincide with Minnesota Extension recommendations for residential fertilizer application.[40] However, no application data from the residential area were collected to support this theory. Additionally, the volume of discharge water at the outflow of the watershed was always greater than the inflow volume (Table 3), promoting dilution. Dilution of NO_3-N during months with higher stream flow volumes would also decrease the concentration of NO_3-N in the discharge compared to the inlet.

Nitrogen loading. Greater nitrogen mass losses in the stream flow were measured in early spring and fall. Early spring losses are related to nitrogen application, precipitation and snow melt, while late fall losses result from wetter conditions, cool temperatures, and excess precipitation. The monthly median mass loss of NO_3-N and TN are highest in May, September, and October (Fig. 5). Greater losses in late April and May are associated with greater nitrogen fertilization rates, extent of application, and greater discharge and precipitation volumes (Fig. 2 and 5). In September and especially October the greater discharge rates and reduced nitrogen demand by the turf lead to greater mass losses of residual nitrogen in the senescing turf, thatch, and soil. Greater discharge rates in May, September, and October result from the combination of increased levels of precipitation and discharge associated with reduced ET and cooler temperatures as well as slower turf growth rates. During late September and October, the turf is entering dormancy with reduced ET and nutrient uptake demand. The less dense turf during initial green up in May and start of dormancy in September and October increases the exposure of the thatch and top soil (A-horizon) to runoff and surface transport of nitrogen. Late summer and fall core aerification with residual plugs left on the surface also increases soil and thatch exposure to runoff losses of nitrogen.

In contrast, despite higher application rates and discharge concentrations in June, July, and August, mass losses of nitrate (<0.1 kg ha^{-1}) and TN (<0.5 kg ha^{-1}) are relatively low (Fig. 5). The summer months have active turf growth, efficient nutrient uptake, and high ET rates resulting in low discharge volume and reduced exposure to nitrogen losses (Fig. 2 and 5).

One metric often used to assess chemical losses is the percentage of applied material that is recovered in the runoff or discharge. For NCC, the mean annual NO_3-N load represented 1.7% of the applied nitrogen while the average annual TN load represented 10.7% of the applied nitrogen. The TN captured in the discharge waters was comparable to the 5% TN reportedly recovered for two golf courses in Canada,[41] but substantially less than the 32% recovered in drainage waters on a course in Japan.[22]

Phosphorus concentration. The median annual DRP and TP concentrations measured in the course outflow were significantly greater than those measured in the inflow. This indicates that course management as affected by runoff was responsible for adding both soluble and total phosphorus to the stream. The concentrations measured on this course were on the lower end of phosphorus concentrations reported for multiple turf studies.[42] The majority of all phosphorus was applied to the golf course in May, although the greatest concentrations were not measured until July, August, and September when flows were less. This inverse pattern between median DRP concentrations measured at the outflow and discharge suggests that DRP loss may be more related to irrigation and subsequent subsurface drainage rather than surface runoff. A similar pattern was observed for TP as well.

Phosphorus loading. Differences in annual export of DRP and TP were attributed to the discharge volume and application rate. A considerable reduction in phosphorus application was noted between the periods of 2003–2005 and 2006–2008. The reduction in phosphorus application resulted in less phosphorus loss per unit of runoff during the latter time period. This reduction was realized even though discharge volumes were greatest in 2007 and 2008. Additionally, the findings were consistent with studies that suggest a reduction in phosphorus application will result in reduced phosphorus losses.[42]

An investigation of the temporal distribution of phosphorus losses reveals that median mass and peak losses of DRP and TP were greatest in May, September, and October. Greater May losses were attributed to the period of primary application (Fig. 6) and hydrology. In May, the winter thaw is subsiding, leaving moisture in the soil profile at or near field capacity. Additionally, May corresponds to the first peak of the bimodal rainfall/runoff period (Fig. 2) and ET is not great during this time period. Additionally, on average 45% of all phosphorus application in any one year was applied in the first month of the growing season, usually May. The combined effect of management and natural climate conditions leads to greater phosphorus transport during the early growing season.

September and October losses were speculated to be the combined result of hydrology, course management, and turfgrass physiology. The second peak in the bimodal rainfall distribution occurs in September and October, leading to wetter conditions conducive to greater runoff volumes. Course aeration is usually completed during this time window as well. Aeration exposes the phosphorus rich thatch and topsoil to runoff. Exacerbating the hydrology and management issues is the turf physiology. Phosphorus utilization during September and October would be less since the plant is not growing rapidly. Additionally, phosphorus loss from senescing vegetation would occur during the latter portion of this time frame. Conversely, the months with active turfgrass growth and reduced discharge, June, July, and August, have reduced phosphorus losses.

The DRP load recovered in the NCC discharge waters represented 2.6% of the applied elemental phosphorus, while TP losses totaled 4.6% of the applied phosphorus. The findings from NCC were comparable to but greater than the 2% phosphorus recovery from two golf courses in Canada,[41] but markedly less than the 14% reported for a golf course in Japan.[22]

Comparison to turf, agricultural, urban/suburban, and forest nutrient losses

The median NO_3-N export coefficient (annual mass loss) from NCC was comparable to coefficients reported for forested and grassland/rangeland catchments but less than NO_3-N losses documented from other golf course studies as well as urban/suburban and agricultural watersheds (Fig. 8). Similarly, the median NO_3-N concentration measured in the discharge water at the outlet of the mixed use watershed in this study was comparable to concentrations for forested, golf course, and urban watersheds, less than NO_3-N concentrations from pastures/rangelands and considerably less than NO_3-N concentrations collected from crop production agricultural catchments (Fig. 9). Median TN loads measured from the NCC golf course watershed were greater than like loads from forests and pasture/rangelands, comparable to urban/suburban losses, and approximately 50% less than loads reported from other golf course and crop production agriculture watershed scale studies (Fig. 8). In contrast, the median TN concentration from the mixed use watershed here was comparable to concentrations documented for forests, pasture/grassland/rangeland and golf courses, but considerably less than median concentrations from urban/suburban and crop production agriculture (Fig. 9).

The median DRP export coefficient for this study was comparable to export coefficients reported for forests, urban/suburban, and crop production agriculture watersheds (Fig. 9).

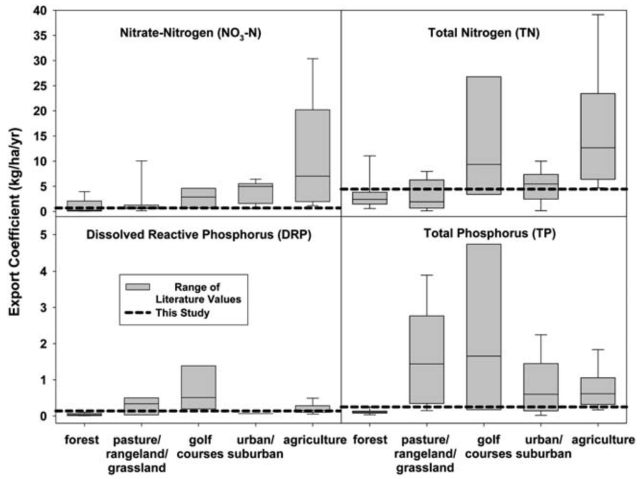

Fig. 8 Comparison of NO_3-N, TN, DRP, and TP export coefficients measured in this study (dashed line) to the range of export coefficients presented for different land uses (box and whiskers plots). The range of literature values was determined from multiple studies (not all studies contained data on each pollutant or land use).[22,23,33,34,41–75]

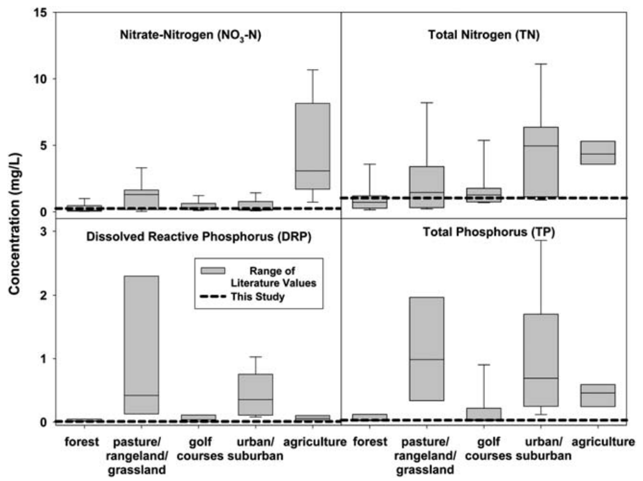

Fig. 9 Comparison of NO_3-N, TN, DRP, and TP concentrations measured in this study (dashed line) to the range of concentrations presented for different land uses (box and whiskers plots). The range of literature values was determined from multiple studies (not all studies contained data on each pollutant or land use).[20–23,33,34,41,49,51,53,55,60–62,65,68,70,71,73,76–85]

In contrast the DRP export coefficient in this study was less than like coefficients reported for other golf courses and pasture/rangeland watersheds (Fig. 8). With respect to concentration, the median DRP concentration measured at the outlet of the mixed use watershed was comparable to documented concentrations for forests, other golf courses, and agriculture. DRP concentrations recorded for pasture/rangeland and urban suburban catchments were considerably greater (Fig. 9). The NCC median TP export coefficient was greater than TP losses for forested lands but less than losses reported for pasture/rangeland, other golf courses, urban/suburban, and crop production agriculture (Fig. 8). In contrast the median NCC TP concentration was comparable to concentrations from forested and other golf course watersheds but substantially less than concentrations from pasture/rangeland, urban/suburban and crop production agriculture (Fig. 9).

Water quality impacts and BMPs

Water quality standards for nitrogen have generally centered on the USEPA[86] established drinking water standard of 10 mg L^{-1}, even though many of the streams being referenced do not serve as drinking water supplies. More importantly, sustainability of aquatic life may be directly affected by the nitrogen concentrations leading to accelerated algal growth. Mallin and Wheeler demonstrated that nitrate-nitrogen concentrations as low as 50 to 100 μg L^{-1} contribute to eutrophication of marine estuaries.[20] Similarly, TN concentrations as low as 1 to 2 mg L^{-1} will promote and sustain algal growth.[38]

In the immediate study, no measured NO_3-N concentration approached the drinking water standard. Maximum NO_3-N concentration at the inflow and outflow was 1.9 mg L^{-1}. Even though the maximum NO_3-N concentration did not approach the drinking water standard it was substantially greater than the 0.1 mg L^{-1} demonstrated to lead to eutrophic conditions in marine estuaries.[20] The median NO_3-N concentrations (0.28 mg L^{-1} for inflow and 0.25 mg L^{-1} for outflow) also exceeded the 0.1 mg L^{-1} suggested level.[20] In fact, 85% of all inflow ($n = 1014$) and 78% of all outflow ($n = 1317$) NO_3-N concentrations exceed the 0.1 mg L^{-1} threshold.[20] Similarly, TN concentrations in this study often exceeded the 1 to 2 mg L^{-1} suggested by Walker and Branham to promote algal growth.[38] Twenty-four percent of the inflow and 53% of the outflow TN concentrations were greater than 1 mg L^{-1}. Only 2% of the inflow and 1.5% of the outflow samples exceeded the 2 mg L^{-1} level.

Water quality criteria related to phosphorus have not been established. However, USEPA offered the following criteria to guard against algal growth: 0.1 mg L^{-1} for streams not directly discharging into lakes, 0.05 mg L^{-1} for streams discharging into lakes, and 0.025 mg L^{-1} for lakes or reservoirs.[86] Koehler *et al.* suggest these values serve as upper limits to protect against algal growth.[15] More recently, Correll indicated that the 0.1 mg L^{-1} phosphorus concentration may be extremely high for streams and reservoirs and suggested that 0.02 mg L^{-1} total phosphorus could be problematic for promoting algal growth.[87]

At NCC, phosphorus concentrations often exceeded the USEPA 0.05 mg L^{-1} recommendation for streams discharging into lakes or reservoirs.[86] Two percent of the inflow DRP samples exceeded the 0.05 mg L^{-1} recommendation, while 13.2% of the outflow DRP concentrations exceeded the 0.05 mg L^{-1} threshold. This suggests that golf course nutrient applications resulted in additional DRP reaching the stream. When considering the Correll suggested level of 0.02 mg L^{-1} TP, 94% of the inflow samples and 97% of the outflow samples met or exceeded the level.[87] These findings highlight the difficult challenge to reduce concentrations to natural environment levels and also suggest that even background levels in the glaciated upper Midwest may exceed recommendations.[88] In the NCC study, the amount of phosphorus fertilizer has been significantly reduced since 2006 (Table 2). However, once soils become saturated with precipitated phosphorus, any additional phosphorus is more readily available for loss in surface runoff.[89]

Development of integrated management plans and implementation of best management practices (BMPs) may reduce the environmental footprint of golf course management. BMPs such as buffers, wetlands, fertilizer formulation, placement, and timing have demonstrated effectiveness at reducing nutrient losses.[24] Use of slow release nitrogen formulations significantly reduced both leaching and surface runoff losses of nutrients.[90,91] Nutrient placement into the thatch and soil through irrigation has been shown to reduce runoff losses of phosphorus by 10.4%.[92] Cole *et al.* demonstrated that greater buffer lengths have a greater capacity for reducing nutrient losses.[93] Implementation of buffers with graduated heights reduced nitrogen losses by 17% and phosphorus losses by 11% when compared to a single buffer height.[94] Bierman *et al.* suggested that phosphorus losses can be reduced by adhering to soil test recommendations and avoiding fall applications.[95] Routing surface and subsurface drainage waters through wetlands may also significantly reduce nutrient export from the managed turf.[15]

Summary and conclusions

NO_3-N, TN, DRP, and TP concentrations and loading were measured during the active hydrology period of April–November from 2003 through 2008 at Northland Country Club (NCC) in Duluth, MN to quantify surface runoff losses and their relationship to application. Concentrations were measurable at both the inflow and outflow sites from April through November. Outflow concentrations generally exceeded inflow concentrations suggesting that fertility management was responsible for increasing stream concentrations. Export coefficients or mass losses were always greater at the outlet compared to the inlet and comparable to other land use categorizations.

Seasonal variations in nutrient concentrations and loading were apparent for all nutrients and a function of hydrology, application timing and rate, and turfgrass physiology. Concentrations were generally less than concentrations from other land uses. Several recommendations for nutrient concentrations have been offered to guard against the promotion of eutrophic conditions. Using the more conservative recommendations, significant numbers of inflow and outflow concentrations at NCC exceed those thresholds. Phosphorus tended to exceed the recommendations more frequently than nitrogen.

Although nitrogen management appears to be less of a concern on this course, phosphorus concentrations and mass losses resulting from past and current applications remain significant issues. Despite the relative immobility of phosphorus in soil, phosphorus losses in stream discharge observed in this study suggest that the turf established on fine textured soils has the potential for small, but significant contributions to surface waters.

Adopting conservation practices aimed at reducing their off-site transport is necessary. Reductions in application to soil test recommendations, especially phosphorus, and implementation of other best management practices, such as timing of nutrient application, judicial use of fall fertilization, and monitoring irrigation practices in relation to timing of nutrient loss, will further reduce the offsite transport of nutrients from managed turf watersheds.

Acknowledgements

The authors would like to acknowledge the assistance of Sara Beth Scadlock, Ivy Leland, Emily Burgess, and Heather McMains in the data collection and processing necessary to complete this manuscript. Without their dedication, perseverance, and attention to detail this study would not have been possible. We acknowledge and sincerely thank Ms Ann Kemble and Mr Jeff Risley for their technical support with respect to sample preparation and to Mr Eric Fischer for his analytical expertise. The authors are also indebted to Dave Kolbry (past superintendent), Christopher Tritabaugh (current superintendent), and Jacob Ryan (current assistant superintendent) for granting us access to the course and sharing their management strategies and records. We would also like to thank the members of NCC for their insight into recognizing the importance of this research and their willingness to permit us to conduct this study on their course. We also acknowledge and thank the US Golf Association Green Section for their support and financial contributions to the study.

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